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Climate-based site selection for a Very Large Telescope using GIS techniques

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1. Introduction

Astronomical research at present requires that a telescope with an aperture diameter of between 50 and 100 metres be constructed within the next 10 years or so. This new generation of telescopes will be called OWL (Overwhelmingly Large), and it represents one order of magnitude increase in size over today's telescopes. Selection of an ideal site for this giant telescope is dependent on many climatological, meteorological and topographical parameters (Grenon 1990). Among these are cloud cover, atmospheric humidity, aerosol content, airflow direction and strength, air temperature, topography, and seismicity. Even relatively minor changes in weather patterns can have a significant effect on seeing conditions. (Beniston et al. 2002).

A composite database has been designed and built for the site selection task at the Department of Geosciences, University of Fribourg in Switzerland. The climatological database is mainly composed of ECMWF (ECMWF 1997) and NCEP-NCAR (Kalnay et al. 1996) reanalysis data at a global resolution of between 1° and 2.5°. Using a Java computer language based interface, programmed in GIS fashion, all of this relevant information can be assessed in order to find the best possible sites for the new telescope. Perhaps the most important variable for site selection is the interaction between airflow and topography, as atmospheric turbulence greatly affects the image quality produced by the telescope.

A preliminary version of the interactive GIS interface and database is available on the worldwide web, accessible by standard browsers with a Java-2 Runtime Environment. Password protection is enabled for security reasons. The Java-based code means that the interface can also be saved as a stand-alone application on CD-Rom.

2. Description of the database

For the most rigorous and best possible site selection process, a lengthy and detailed climatic database is needed. Added to this is the fact that global climate is changing and it will continue to do so throughout the twenty-first century (IPCC 2001). An ideal site in today's climate may not prove ideal within 30 to 50 years. Therefore, future climate information (taken from the output of General Circulation Models) is also of great interest in the site selection process.

The historical climatological database is composed mainly of 'reanalysis' datasets from the European Centre for Medium Range Weather Forecasting (ECMWF) and the National Center for Environmental Protection/National Center for Atmospheric Research (NCEP-NCAR). A reanalysis is a look backwards in time, recreating the weather charts again for each time step in the past, but using the same climate model to do so. Previously, 'apparent' changes occurred in the climate system when new data assimilation techniques or more accurate models were introduced. This led to spurious trends in climate. The reanalysis procedure avoids these problems by using the same climate model to recreate the weather patterns in the past. The only source of error will derive from the spacing and availability of the original weather observations.

Typically, both the ECMWF and NCEP-NCAR reanalysis data have a global resolution of between 1° and 2.5° latitude/longitude. Although a resolution of 1° latitude still represents a distance of more than 100 km on the ground, this is the best possible resolution available in current reanalysis projects. This resolution will probably increase with more advanced reanalysis projects in the future. Currently, the NCEP-NCAR reanalysis project spans the period from 1948 to the present (see http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml for more information). The ECMWF reanalysis project (ERA-15) spans a shorter period from 1979 to 1993 (http://www.ecmwf.int/research/era/ERA-15/index.html), although a new ERA-40 reanalysis project is in the process of being made available from ECMWF, spanning the period from 1957 to 2001 (see http://www.ecmwf.int/research/era/). At

Table 1. *NCEP/NCAR reanalysis datasets used*

NCEP/NCAR data			
File specification	Resolution	Period	File description
air2m.mon.mean.nc	T62 Gaussian grid (192 × 94 pts ∼ 1.865°)	1948 – present	*Statistic*: air 2-m temperature monthly mean. *Level*: 2 m *Unit*: K
olr.mon.mean.nc	2.5°	1948 – present, but gap (1978)	*Statistic*: outgoing longwave radiation monthly mean. *Level*: other. *Unit*: not specified, probably W/m^2
pr_wtr.mon.mean.nc	2.5°	1948 – present	*Statistic*: monthly means of precipitable water vapour *Level*: integrated all levels as one. *Unit:* kg/m^2

Table 2. *ECMWF reanalysis datasets used (ERA-15)*

ECMWF data (ERA-15)			
File specification	Resolution	Period	File description
Tcc	2.5° (144 by 73 grid points)	1979–1993	*Statistic:* total cloud cover (as a fraction between 0 and 1). Fields of quantities accumulated over 24 h periods centered on 12 UTC.
Surface	2.5° (144 by 73 grid points)	1979–1993	*Statistic:* U & V components of wind (m/s) at 10 m level. Fields of quantities centered on 12 UTC.
850 mb	2.5° (144 by 73 grid points)	1979–1993	*Statistic:* U & V components of wind (m/s) at 850 mb level. Fields of quantities centered on 12 UTC.
200 mb	2.5° (144 by 73 grid points)	1979–1993	*Statistic:* U & V components of wind (m/s) at 200 mb level. Fields of quantities centered on 12 UTC.

Table 3. *TOMS aerosol datasets used*

TOMS Data			
File name	Resolution	Period	File description
gmMMYY.n7a	1.25° by 1.0° (288 by 180 grid points)	1978–1993 (Nimbus 7)	*Statistic:* TOMS aerosol index as calculated from Nimbus-7 satellite (n7a) and Earth Probe (epa).
gmMMYY.epa		1996–1999 (Earth Probe)	

a later stage of the OWL project, it is hoped to include the new improved ERA-40 dataset.

The full listing of meteorological and climatological parameters used in this study are given in Tables 1 to 3. Of primary importance are variables such as cloud cover, atmospheric humidity, airflow direction and strength, aerosol content, and air temperature. Seismicity and topographic layers will be added to the database at a later stage. Other secondary or computed variables (e.g. severe weather indices) may also be added. All data have been converted to single column ASCII format.

Air temperature (air2m) is provided by NCEP-NCAR as monthly means of 2-m air temperature from 1948 to the present. Astronomical optics and engineering are sensitive to extremes of temperatures, so it may be necessary to include higher frequency air temperature datasets at a later stage of this project.

Outgoing Longwave Radiation (olr) is an indirect way of measuring cirrus clouds, which can be detrimental to astronomical viewing. Cirrus clouds strongly trap infra-red radiation, so negative anomalies of outgoing longwave radiation indicate a higher than normal presence of cirrus clouds. Large positive and negative anomalies of outgoing longwave radiation in the tropics are related to El Niño/La Niña weather patterns, which have been shown to affect astronomical viewing quality (Beniston et al. 2002).

Precipitable water vapour (pr_wtr) is provided as a monthly mean of integrated total column precipitable water vapour in kg/m^2 (which is equivalent to millimetres). It is the mean total amount of water that could be precipitated from the atmosphere. Values typically range from a few mm in cold regions to over 50 mm in the tropics. An excellent site for OWL would be in an area with a mean precipitable water content of

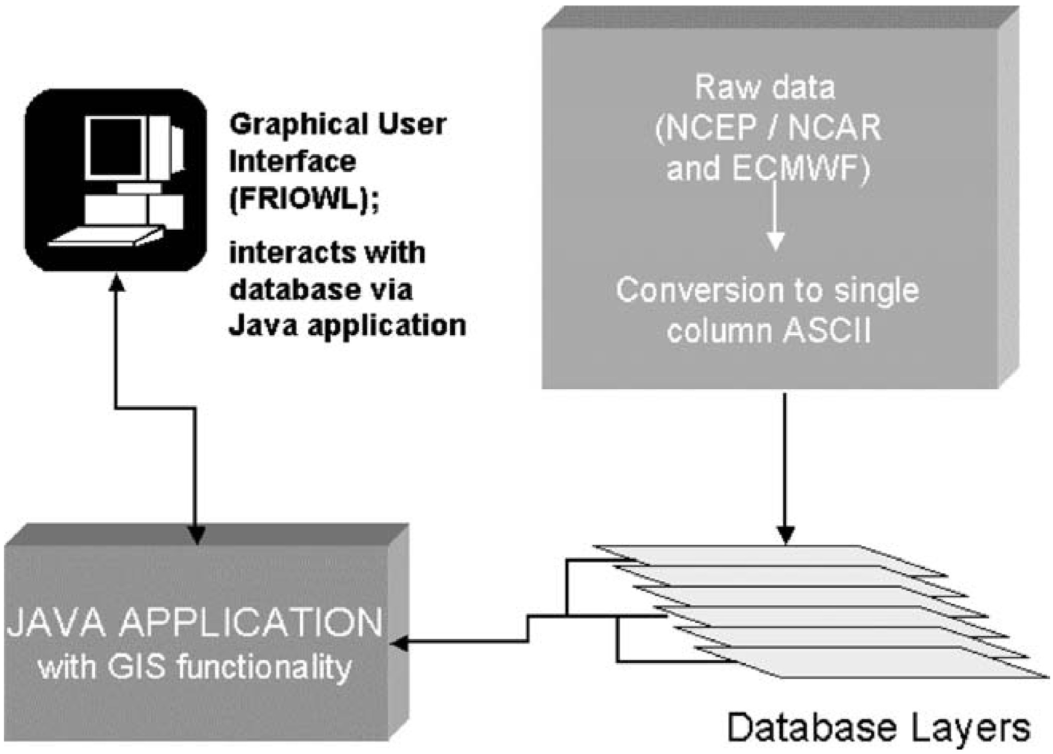

Figure 1. *The design of the FRIOWL interface and database.*

less than 3 mm throughout the year. In practice, such areas are only found in high altitude deserts or in the Antarctic.

Total cloud cover (tcc) information is provided by the ERA-15 dataset at a global resolution of 2.5° latitude/longitude. The data is calculated as the mean fraction of cloud cover (all levels) between 0 and 1. Cloud cover has obvious detrimental effects on astronomical viewing, blocking the incoming visible radiation. Preferential sites should have a cloud fraction of 0.1 or less.

Atmospheric turbulence is one of the most important criteria in the site selection process, so the interaction between airflow and topography will need to be ascertained in great detail. Turbulence is a complex phenomena, acting on many different scales. However, we will initially investigate turbulence only at broad scales, such as that related to the jetstream winds. Therefore, daily wind direction and strength data have been obtained for the 200 mb level from the ERA-15 period (1979–1993) at a grid resolution of 2.5°. Surface and 850 mb level winds will also be included in the database in order to look at lower atmospheric effects.

Atmospheric aerosols also deteriorate astronomical viewing, as they can both absorb and scatter lights of different wavelengths. Therefore, Total Ozone Mapping Spectrometer (TOMS) aerosol data is being used in the OWL project database. The data are available from NASA (see http://toms.gsfs.nasa.gov/aerosols/aerosols.html) at a grid resolution of 1.25° × 1.0°. Owing to the position of the TOMS satellite, however, data is only available for latitudes between 60°N and 60°S. The TOMS aerosol index is related to aerosol optical depth, which, in turn, is a measure of how much light airborne particles prevent from passing through a column of atmosphere. Typically, an aerosol index of less than 0.1 indicates a crystal clear sky with maximum visibility, whereas a value of 4 indicates the presence of aerosols so dense you would have difficulty seeing the mid-day sun. An OWL site should, therefore, have a very low mean aerosol optical depth value.

3. Description of the interface

A user-friendly interface has been designed at the University of Fribourg (Switzerland), which combines the ease-of-use of a GIS application together with the climatological and geomorphological database described above. The Java computing language has been chosen for this task not only because it can help to create portable, cross-platform and user-friendly applications, but also for its ability in running GIS-like functions and tasks. During the past year, the interface (which has been named 'FRIOWL', based on a combination of the names 'Fribourg' and 'OWL') has been progressively developed by scientists at the Departments of Geography and Informatics. It continues to undergo refinement and improvements, according to the needs specified by scientists of the main funding agency (the European Southern Observatory, based in Munich, Germany). A decision on the telescope site does not need to be taken until the year 2005.

A schematic diagram of the design of the FRIOWL interface and how it interacts with the database is shown in Figure 1.

COLOUR

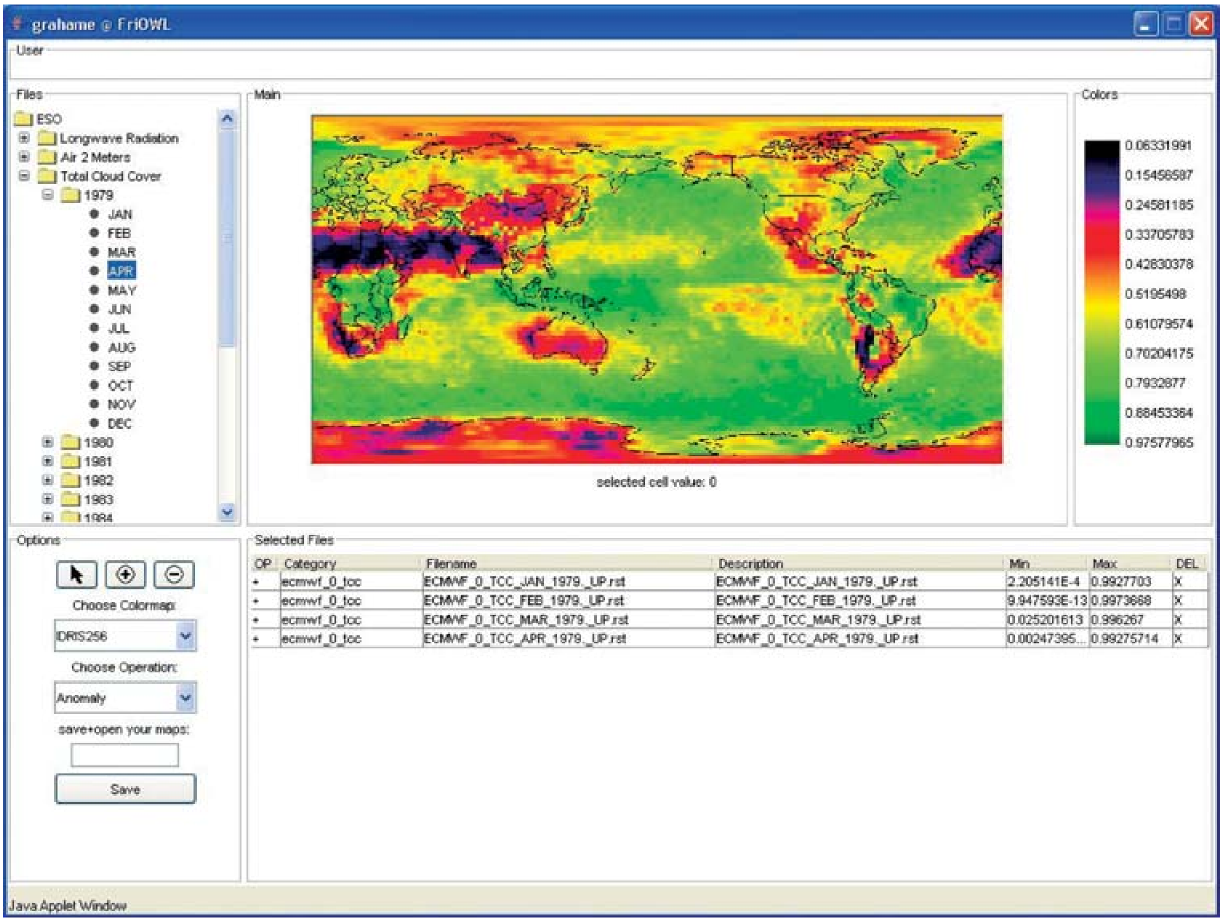

Figure 2. *The FRIOWL user interface after startup.*

The FRIOWL application can be run either from executable file on a CD-Rom, or directly on the internet using a browser with Java-2 runtime environment installed. The internet version initially presents an embedded Java applet on a simple web page to prompt the user to enter a recognised username and password, for security reasons. The CD-Rom version bypasses this verification procedure, and allows direct access to the interface startup by simply clicking on an icon. The CD-Rom is available for PC, Macintosh and Sun-Solaris platform users.

The interface is a Java application (not an applet) and once started, it greets the user with a standard graphical user interface consisting of a main window with several sub-windows and frames, such as that shown in Figure 2.

The interface is relatively easy to use. It consists of five frames within one user window. The top-left frame houses the database tree, which the user can expand using simple click-and-point techniques (this frame is called 'Files'). To the right is the main user window-frame (called 'Main'), which visually plots the data file(s) that has been chosen. A chosen palette legend (frame called 'Colors') lies on the far right. Below this is the user files box (frame called 'Selected Files'), in which a list of the currently chosen files reside. At the bottom-left of the window is the 'Options' frame, where the user can change his/her options or choose new operations (such as zoom, change colour palette, or choose a operation).

Navigation is simple: the user expands the database by simply clicking on a file of interest in the 'Files' frame. When a file is clicked, its name appears in the working frame ('Selected Files') below to the right. Each main folder has a series of subfolders, and the data files are listed according to the month and year. The user can then interrogate his/her chosen files using the options menu from the 'Options' frame.

There are several different operations that can be performed on the data and the maps displayed. First, using the plus and minus buttons, the user can zoom into areas of interest on the chosen map. Secondly, he/she can choose different colour maps or palettes to display the maps. These colour maps are based on those provided by the software IDRISI Release 3.2 (Eastman 1987–2020). Thirdly, he/she can choose an operation. These are simple mathematical operations performed on the selection of maps in your user-window. As of January 2004, the following operations are currently enabled on FRIOWL:

(a) AVERAGE: the arithmetic average of all chosen user-maps is displayed

(b) SUM: the arithmetic sum of all chosen user-maps is displayed
(c) MAX: the maximum pixel value of all pixels of all chosen user-maps is displayed
(d) MIN: the minimum pixel value of all pixels of all chosen user-maps is displayed
(e) ANOMALY: this is a special feature; which displays the average of all certain selected maps, minus the average of all certain non-selected maps. In other words, it displays the mean of a set of maps, subtracted from the mean of another set of maps (i.e. the anomaly). You need to have a range of maps selected in the 'Selected Files' window in order for this option to work.

The user can save the resulting maps as a single new 'composite' map. This avoids having to click on the all the files again in the database window. The file is saved locally on the computer when using the CD-Rom, but on the server (under your username) if using the internet. Therefore, the user can reaccess previously saved files at a later time, if so desired.

All the above functions allow manipulation of the climatological and geomorphological database in order to find the best possible sites for the future OWL telescope. For example, we can narrow down those locations in the world where cloud cover is less than 0.1, where jetstream winds are predominately light, and where total column precipitable water content is less than 3 mm.

More detailed GIS tasks such as overlaying these maps and the use of weighting functions for different variables are planned in the near future. This will help in the search for an ideal telescope site, as different levels of importance will be given to different climatological and geomorphological variables. So far, the Java programming language, in connection with the global climatological database, has demonstrated its ability to meet these needs and proved that it can act as a true Geographical Information System.

Finally, it is important to ascertain the effect of global warming on potential sites. It is therefore planned to update the database with future climate data, using the Canadian Climate Model available at the University of Fribourg (Laprise et al. 2003). High resolution modelling of the critical parameters at preferred sites under future climates is also planned.

4. Conclusions

We have shown that the Java computing language can create user-friendly interfaces, as well as undertake simple mathematical and GIS tasks with a climatological and geomorphological database. Different data layers can be interrogated in order to find possible sites for the new telescope. Resulting maps can be displayed visually in an attractive and colourful manner. More advanced GIS operations and spatial analyses are planned in the future, such as contextual procedures based on the different climatological and geomorphological layers. It is also hoped to adapt the interface to a larger database, such as one using enhanced resolution future climate information for potential telescope sites.

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